DISAPPEARANCE OF THE HELIOSPHERIC SECTOR STRUCTURE AT ULYSSES

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In May, 1993, the heliospheric current sheet (HCS) ceased to be seen by the Ulysses spacecraft at a heliocentric latitude of -30° S and distance of 4.7 AU. The disappearance of the HCS coincided with the solar wind speed remaining >560 km/s and with the disappearance of one of four interaction regions previously seen on each solar rotation. The heliographic latitude of the disappearance of the HCS at Ulysses was 11° equatorward of the latitude of the magnetic neutral sheet at the source surface at 2.5 solar radii, and it occurred a half year earlier than predicted on the basis of the persistence of the time profile of the neutral sheet tilt from one solar cycle to the next.

INTRODUCTION

At the beginning of June, 1993, the Ulysses spacecraft was near 4.7 AU and traveling toward the south solar pole at an average rate of -2° heliographic latitude per month. Of scientific interest is the latitude at which the spacecraft passes south of the heliospheric current sheet (HCS) and only a single magnetic polarity, corresponding to that of the Sun's south magnetic pole, is observed. We have been watching the incoming Ulysses data for evidence of this event.

As reported here, the two-sector pattern normal for the present phase of the solar cycle disappeared between April and June, 1993, when Ulysses exceeded 30° south latitude. The Ulysses observations complement those of Pioneer 11 which recorded the disappearance of the sector structure at 16° latitude in 1975-6 [*Smith* et *al.*, 1978] and again in 1985-6, also at ~ 16° [*Smith et al.*, 1988; *Smith*, *1989]*, and at Voyager 1 in 1986-8 at 27.8-30.8° [*Ness and Burlaga*, 1993]. Thus, the inclination of the current sheet to the solar equator has decreased to low values in three successive solar activity minima.

Observations of the maximum latitude of the current sheet, roughly equivalent to its inclination, are useful. They provide a test of how accurately the neutral sheet computed on the solar source surface coincides with the current sheet observed by heliospheric spacecraft [*Hoeksema*, *1986]*. A related issue is the possible distortion of the global shape of the current sheet as a result of the radial evolution and dynamics of the solar wind *[Thomas and Smith,* *1981]*. Of further interest is the precise relation between the changing current sheet inclination and the phase of the solar cycle. A recently published prediction as to when Ulysses would exceed the maximum latitude of the HCS is based on the systematic evolution of the neutral sheet over the course of a solar cycle [*Suess et al.*, 1993].

ULYSSES OBSERVATIONS

Ulysses left the vicinity of Jupiter in February, 1992, headed for the Sun's south polar region [*Wenzel et al.*, 1992]. On 9 June, 1993, Ulysses was at a heliographic latitude of -32°, the most extreme latitude reached by any spacecraft. At that time the spacecraft was 4.7 AU from the Sun.

The observations reported here were obtained by the magnetic field investigation described in detail in *Balogh et al. [1992]* and the solar wind plasma experiment described in *Bame et al. [1992]*. A combination of factors contribute to the high accuracy of the field measurements even in the weak fields (B < 1 nT) which are characteristic of the heliosphere beyond several AU. The low-level spacecraft-generated magnetic fields, the location of the dual magnetometer sensors on a long boom, accurate determination of the three zero levels using the spin of the spacecraft and the variance technique [*Belcher*, *1973; Davis et al., 1973; Hedgecock*, 1975], frequent in-flight calibrations, and the stability of the vector helium magnetometer all contributed to that end.

Ulysses has benefited greatly from a mission operations design based on use of an on-board data storage unit (tape recorder) and a single downlink per day to maintain data continuity. The advantages are evident in Figure 1 which shows 6-hour averages of the field azimuth angle ϕ in heliospheric coordinates, the field *magnitude* B, and the solar wind speed V (as previously described by *Bame et al.* [1993]). The plots in Figure 1 begin on day 001 of 1993 and end on day 151 (May 30) The middle panel (B) shows a succession of compression and rarefaction regions, while the "square wave" evident in the top panel (ϕ) identifies the magnetic sectors.

The high inclination of the spacecraft's elliptical trajectory makes the Sun's synodic and sidereal rotation periods nearly equal, Solar observations indicate that the sidereal rotation period at the equator (-25 days) increases to -27.4 days at 32° latitude. The rotation period of solar wind features observed by Ulysses is expected to lie between these limits.

For a rotation period in that range, the bottom panel of Figure 1 shows that the solar wind structure was dominated by a large-amplitude stream associated with flow from the south polar coronal hole [*Bame et al.*, *1993]*. Closer examination of the speed profile and of the variation of the field magnitude (middle panel of Figure 1) reveals that there were, in fact, three or four interaction regions per rotation which were characterized by relatively large B and are designated by the letters **a** through **d** in Figure 1. These regions correspond to intervals in which the solar wind speed V was either increasing or approximately constant. The sharp boundaries to the interaction regions were typically a forward and reverse shock pair. The intervening rarefaction regions, in which V was decreasing, are intervals of unusually low and quiet B. The ϕ angle in the top of

Figure 1 shows that only one of the four streams (c) had negative polarity, indicating that it originated in the northern solar hemisphere. The proximity of region c to region **d**, without a marked interval of decreased B between them, shows that they had merged, a not unusual condition at the heliospheric distance of Ulysses.

The last third of Figure 1 reveals the same basic structure as does the first two thirds, with an important exception. Only three interaction regions were present, while the ϕ angle showed only a single, negative sector and the solar wind speed never dropped below 560 km/s. The sector previously associated with interaction-region c disappeared along with the corresponding region of increased B and low speeds.

There are a few brief intervals in the top panel of Figure 1 which could be interpreted as having an ambiguous magnetic polarity. The complete absence of a positive sector is confirmed, however, in Figure 2, which is a histogram of ϕ covering days 078 to 151, 1993. The arrows in Figure 2 denote the parker spiral angle, ϕ_p, based on V = 700 km/s and a solar rotation period of 27.4 days for inward (ϕ = 113°) and outward (ϕ = 293°) polarities. There is no evidence of a peak corresponding to an outward-directed sector.

COMPARISON TO SOLAR OBSERVATIONS

These observations provide another opportunity to test the shape of the HCS as determined by extrapolating the line-of-sight photospheric magnetic field to a surface at 2.5 solar radii and imposing the boundary condition that the field be radial at that distance. The contour along which B = O, the neutral sheet, has traditionally been identified with the HCS. The neutral sheet contours are published by Stanford University in the monthly NOAA *Solar-Geophysical Data* reports. Figure 3 compares the latitude of the HCS observed at Ulysses to the latitude of the neutral sheet on the source surface at 2.5 solar radii. The figure was constructed by using the location of Ulysses and the times and values of the minimum speeds between recurrences of the high-speed stream to estimate (using a constant-velocity approximation) the times of emission and the heliographic latitudes and longitudes of the sources of" the slow wind associated with the HCS. After taking the different longitudes of the sub-Earth and sub-Ulysses points into account, the longitude of each of the HCS source regions was found to be within -45° of the solar longitude at which the neutral sheet on the source surface reached its extremum of southerly latitude for the relevant Barrington rotation. The circles in Figure 3 show those South latitude extremes for each rotation.

The data in Figure 3 indicate that if the latitude of the HCS at ~5 AU were identical to the latitude of the neutral sheet at the source surface, the HCS would have been detected by Ulysses through June 1, 1993. The fact that it was not observed for the periods corresponding to the two points on the right side of Figure 3 indicates that there is some deformation of the HCS 'as it propagates out from the Sun. This deformation was ≥11° (next to last point), but <20° (third point from the right). The deformation is in the sense of a squashing of the wavy HCS.

DISCUSSION

Although it is not obvious from the high-time-resolution data plotted in Figure 3, at the current phase of the solar cycle (approaching solar activity minimum), the tilt of the source-surface neutral sheet, and therefore presumably also the inclination of the HCS, is declining from a value >70° near solar maximum to <15° near solar minimum. The recent disappearance of the HCS at Ulysses is the combined result of that decreasing tilt and the increasing south latitude of Ulysses. These Ulysses results represent the latest instance in which the HCS has dropped below a high-latitude spacecraft and the sector structure has disappeared. Similar disappearances were observed at ~16° latitude by Pioneer 11 in 1975-6 and again in 1986-7. Ness *and Burlaga* [1993] report that from 1986 through 1988 Voyager 1 observed "predominantly" a single negative polarity at latitudes from 27.8 to 30.8°N at distances >25.4 AU. Each instance of the disappearance of the HCS was near solar minimum. This behavior in three successive solar cycles reinforces the presumed dependence of the HCS inclination on the solar cycle and on the tilt of the source-surface neutral sheet, although we have shown that there is some deformation due to stream-stream interactions and/or the latitude gradient of the solar wind speed.

Suess et al [1993] predicted that Ulysses would pass above the HCS in November, 1993. Their approach was based on the observed persistence of the tilt-versus-time profile from one solar cycle to the next. The earlier than predicted disappearance of the HCS at Ulysses can be attributed to a mixture of a faster than predicted decrease in the latitude of the source surface and a deformation of the HCS surface between 2.5 solar radii and ~5 AU.

Will Ulysses now stay above the current sheet all the way to the polar regions? If past experience holds, the inclination of the HCS will decrease steadily and remain low throughout solar minimum and will not be seen again at higher latitudes until after the new sunspot cycle begins.

Acknowledgments. We thank J. Wolf for assistance in preparation of the figures in this paper. Portions of this report present work done at the Jet Propulsion Laboratory of the California Institute of Technology for the National Aeronautics and Space Administration. The Imperial College contribution is supported by the U. K. Science and Engineering Council. Work at Los Alamos was carried out under the auspices of the U. S. Department of Energy with financial support from NASA.

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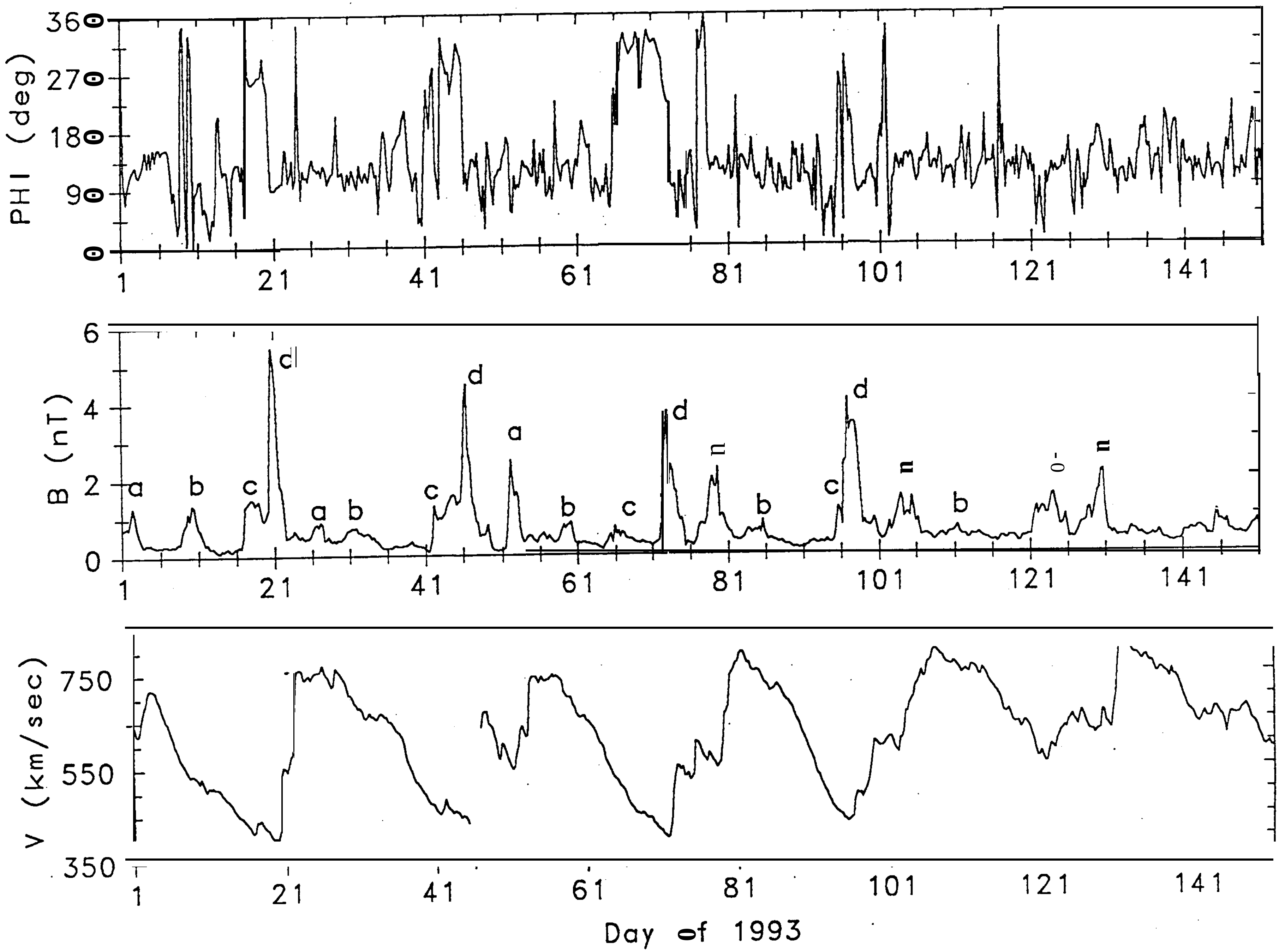
FIGURE CAPTIONS

Fig. 1. Six-hour averages of (top) azimuth angle of the magnetic field in heliographic coordinates, (middle) the field magnitude, and (bottom) the solar wind speed observed by Ulysses in early 1993.

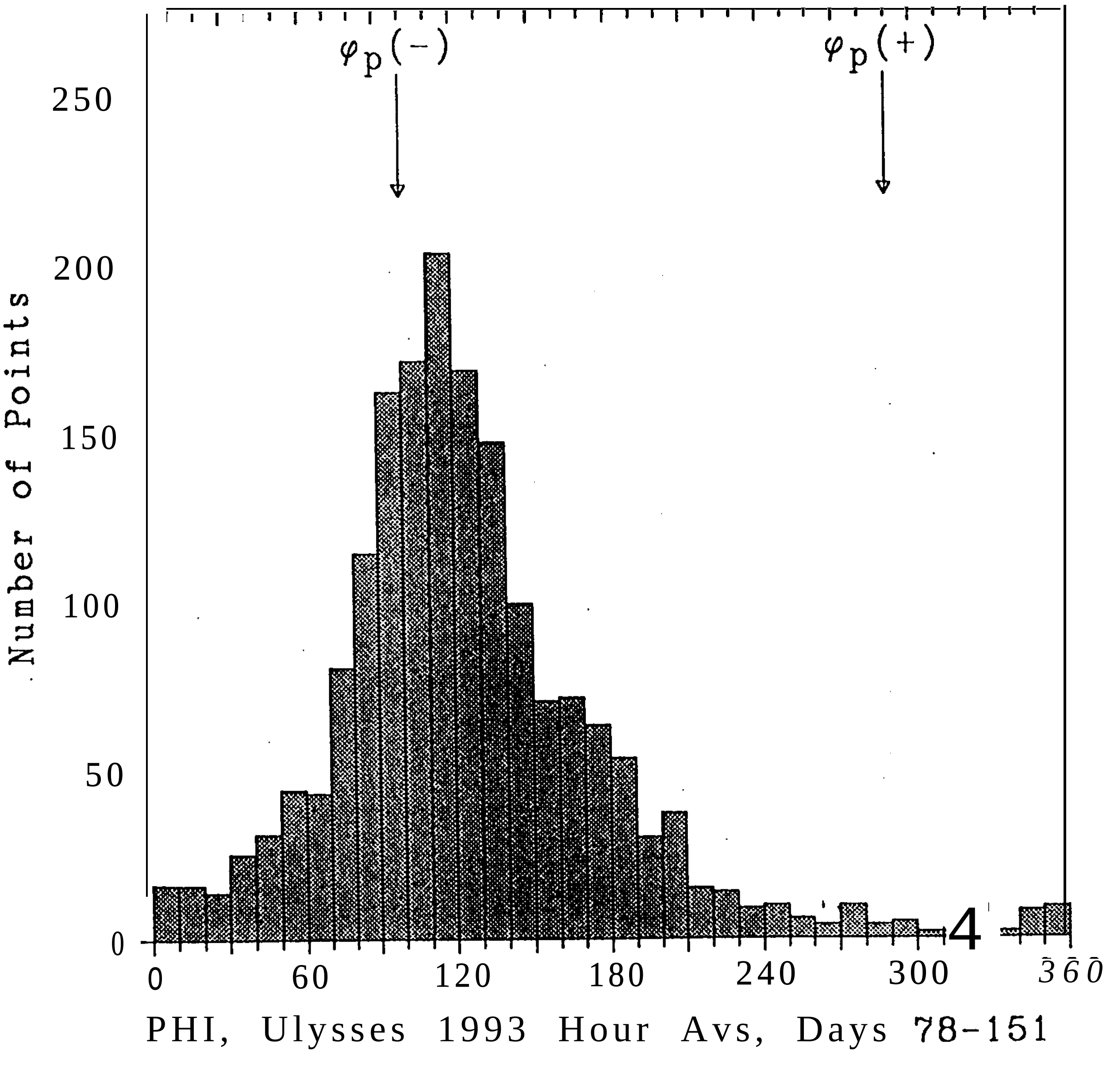
Fig. 2, Distribution of hourly averages of the azimuth angle of the interplanetary magnetic field between days 078 and 151, 1993.

Fig. *3*. The latitudes of the Ulysses spacecraft (+) and the south-most extent of the source-surface neutral sheet (circles) versus the times of minimum solar wind speed mapped back to the Sun.



PHI (deg)
360
270
180
90
0
B (nT)
6
4
2
0
a b c d a b c d a b c d u b c d u b 0 u
V (km/sec)
750
550
350
1 21 41 61 81 101 121 141
Day of 1993

Fig



$\varphi_p(-)$
$\varphi_p(+)$
250
200
150
100
50
0
Number of Points
0
60
120
180
240
300
360
4
PHI, Ulysses 1993 Hour Avs, Days 78-151

Fig 2

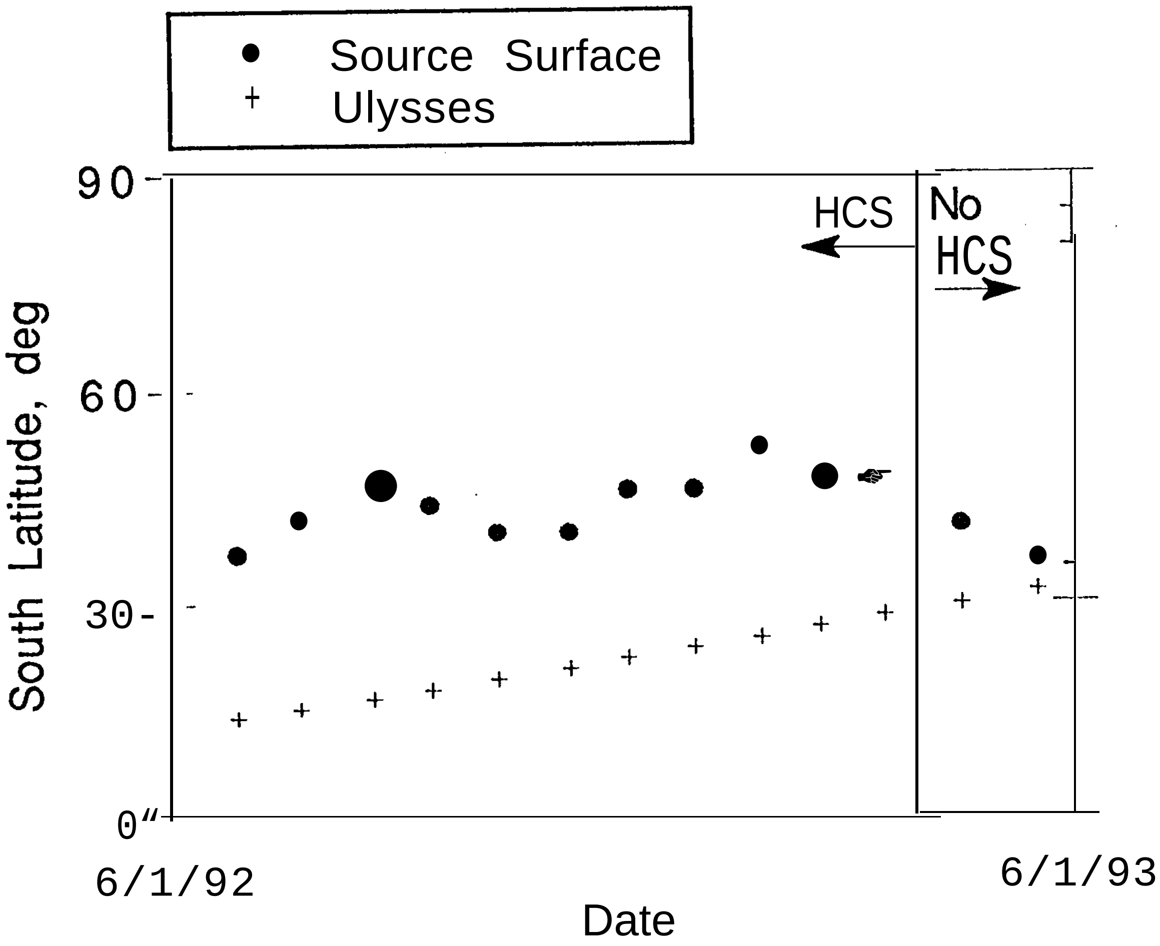

Source Surface
Ulysses
South Latitude, deg
90
60
30
0
HCS
No HCS
6/1/92
6/1/93
Date

Fig 3